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Review and prospect of guidance and control for Mars atmospheric entry

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ABSTRACT

The Mars atmospheric entry phase plays a vital role in the whole Mars exploration mission-cycle. It largely determines the success of the entire Mars mission. In order to achieve a pin-point Mars landing, advanced entry guidance and control is essential. This paper systematically summarizes the past development and current state-of-art of Mars entry guidance and control technologies. More specifically, the Mars entry process and main technical challenges are first introduced. Second, the guidance and control technologies adopted in the past successful Mars landing mission are reviewed in detail. Next, current state-of-art and recent developments of guidance and control for Mars atmospheric entry are summarized at length. The advantages and disadvantages of the various existing methods are analyzed. Lastly, supposing future Mars pin-point landing missions as the potential project application goals, a more comprehensive outlook and prospect for the next-generation Mars entry guidance and control technologies are described.

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Contents

Abbreviations: AFL, astrobiology field laboratory; MER-B, Opportunity; CG, center of gravity; MSL, Mars science laboratory; CGT, command generator tracker; MSMSG, multiple sliding mode surface guidance; DEKF, desensitized extended kalman filter; MSR, Mars sample return; DOF, degree-of-freedom; MOLA, Mars orbiter laser altimeter; DSN, deep space network; MOPSO, multi-objective particle swarm optimization; EAGLE, evolved acceleration guidance logic for entry; MPF, Mars Pathfinder; EDL, entry, descent and landing; NASA, National Aeronautics and Space Administration; ESA, European Space Agency; NLP, non-linear programming; ETPC, entry terminal point controller; NNSMVSC, neural network-based sliding mode variable structure control; GNC, guidance, navigation and control; NPC, nonlinear predictive controller; HERRO, human exploration using real-time robotic operations; PC, polynomial chaos; IMU, inertial measurement unit; PD, proportional-differential; KKT, Karush–Kuhn–Tucker; PEDALS, parametric entry, descent, and landing synthesis; L/D, lift-to-drag ratio; PWM, pulse-width-modulation; LQR, linear quadratic regulator; RCS, reaction control system; Mars-GRAM, Mars global reference atmospheric model; SAMIC, structured adaptive model inversion control; MCD, Mars climate database; SMVSC, sliding mode variable structure control; MEDLI, MSL entry, descent, and landing instrument; SOPSO, single objective particle swarm optimization; MER, Mars Exploration Rovers; UHF, ultra-high frequency; MER-A, Spirit

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1. Introduction

1.1. Past Mars landing mission overview

As the nearest neighbor of planet Earth, Mars has attracted more attention than other planets for decades. In order to obtain the first-hand scientific data of Mars topography and chemical composition, landing a vehicle on the surface of Mars and performing in situ exploration is a prerequisite. Since the 1970s humans commenced Mars landing exploration missions. So far, more than two-thirds of the Mars missions ended in failure, and only seven spacecraft successfully landed on the surface of Mars [1].

The Mars-2, launched by the Soviet Union in 1971, is the first spacecraft that reached the surface of Mars, although it finally crashed on the Martian surface. Mars-3 and Mars-6 also succeeded in reaching the surface of Mars in 1971 and 1973 respectively, but their transmissions soon stopped after landing [2]. NASA launched the Viking-1 and Viking-2 in 1976, and both successfully landed on the surface of Mars [3–6]. Subsequent NASA Mars missions, such as Mars Pathfinder (MPF) [7–17], Mars Exploration Rovers (MER) (including Spirit (MER-A) and Opportunity (MER-B)) [18–24], Phoenix [28–35], and Mars Science Laboratory (MSL) [36–44], incorporated the Mars entry, descent and landing (EDL) technologies qualified by the Viking missions and succeeded in landing on Mars. The European Space Agency (ESA) launched the Mars Express in 2003, and its lander probe Beagle-2 successfully landed north of the equator of Mars, but it fell silent after landing [45–47]. Future Mars landing missions include ESA's ExoMars [48,49], NASA's astrobiology field laboratory (AFL) [50] and Mars sample return (MSR) [51–54], which are expected to be launched between 2016 and 2024.

All Mars landers, except for recent MSL/Curiosity, have flown an unguided ballistic atmospheric entry and adopted the so-called first-generation of landing systems, which aimed at safely landing on Mars without considering the scientific value of landing sites. The next-generation landing system, often called pin-point landing systems, will have the capability of autonomously and safely landing on hazardous sites with high scientific value pre-selected by scientists [55,56]. While the first-generation systems generated a landing uncertainty ellipse in the order of 500 km by 100 km, the next-generation aims for a precision in the order of 10 km, and even down to 100 m [57].

1.2. Mars atmospheric entry phase

Mars entry, descent and landing (EDL) commences at the Mars atmosphere interface with a velocity of around Mach 25 and ends with a safe touchdown, which includes the atmospheric entry phase, the parachute descent phase and the powered descent phase [58]. Fig. 1 shows the sequence of events for a future representative Mars EDL baseline scenario. The entry, descent and landing phases are crucial for a Mars landing exploration mission, which directly determines the success of the entire mission [59–62]. As the extremely important sub-phase of EDL, the Mars atmospheric entry phase begins when the vehicle reaches the Mars atmospheric boundary (about 125 km altitude) and ends at deployment of the supersonic parachute, which lasts about 4 minutes and suffers the worst aerodynamic heating environment during all three sub-phases of EDL [42,59]. The entry vehicle's velocity is reduced from 4–7 km/s to about 400 m/s during the Mars atmospheric entry phase. Therefore this phase is also called hypersonic entry phase [63–66]. The 99% of initial kinetic energy will be consumed during the atmospheric entry phase, and the peak overload and peak heat flux also happen in this phase, which present a huge challenge to designing aerodynamic deceleration, structure and thermal protection system [67–70].

In order to simplify the entry guidance and control system design and enhance the entry reliability, the closed-loop guidance and control systems were not adopted in the previous missions except for the recent MSL/Curiosity [59,72,73]. Most Mars entry vehicles adopted ballistic entry, and there was no aerodynamic lift used in the guidance and control operations. Therefore, the entry and landing error caused by the accumulated navigation error,

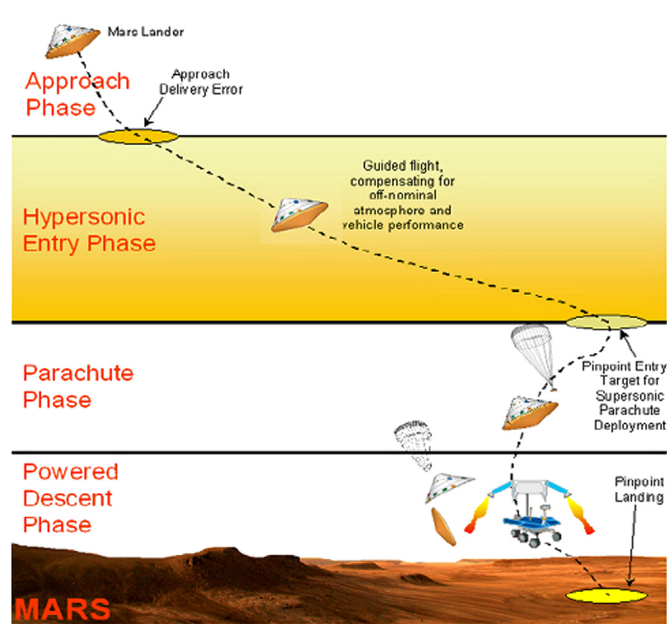


Fig. 1. Representative entry, descent, and landing scenario [71].

uncertainties in the atmospheric density and aerodynamic parameter of entry vehicles cannot be effectively suppressed and reduced, which leads to the larger landing error ellipse in the order of several hundred kilometers [59–62]. In order to achieve the smaller error ellipse and landing spacecraft at a higher latitude region, the closed-loop guidance, navigation and control (GNC) system must be adopted to guide the entry vehicle through the hypersonic phase to the supersonic flight phase. The future Mars lander will adopt the lifting entry body configuration (achieved via the center of gravity offset from the center of pressure) and control the orientation of the lift vector by bank angle modulation. This is very different from the Viking-era landers, which all had performed zero-life ballistic entry, descent and landing and led to larger landing errors [74]. As MSL adopted the first-ever guided ballistic-lifting entry, the entry and landing accuracy had been greatly improved. The Mars entry process of MSL/Curiosity is shown in Fig. 2 [42,44,75].

1.3. Mars atmospheric entry modes

According to the difference in vehicle configurations, how lift is utilized and whether an active guidance method is adopted, the entry modes adopted by the previous Mars landing missions can be broadly divided into three categories: ballistic entry mode, unguided ballistic-lifting entry mode, and guided ballistic-lifting entry mode [76–79]. A ballistic entry trajectory is a trajectory flown with no lift. If the trajectory is flown with lift, but is unguided, it is called an unguided ballistic-lifting entry. In a guided ballistic-lifting entry, the lift vector is oriented to shape the trajectory [80].

In the ballistic entry, there is no aerodynamic control lift available to guide the trajectory and thus reduces the size of the landing ellipse. The navigation accumulated errors and the uncertainties in Mars atmosphere and aerodynamic parameters will lead to a large landing dispersion [81]. MER-A/B, Phoenix and MPF adopted the unguided ballistic entry mode and achieved the successful landing on Mars, which shows that the ballistic entry mode has a good robustness [7,10,12,19,23,25,33]. Though a ballistic-lifting entry configuration was adopted in the Viking missions, there was no active guidance system developed for the Mars atmospheric entry phase. Therefore, Viking is a typical representative of the unguided ballistic-lifting entry mode. During atmospheric entry of both Viking 1 and Viking 2, the lift was not utilized to adjust the entry trajectory, only to keep the stability of the entry vehicles [3,4]. In the case of a guided ballistic-lifting entry, the capsule trajectory can be adjusted to reduce the landing error by the reaction control system (RCS), which uses small thrusters to modify the attitude of the vehicle and direct the lift vector in order to control the vehicle's flight path [79,82]. In addition to reducing the size of the landing ellipse, lift can also be used to improve the elevation of landing sites [213,214]. MSL/Curiosity is a typical representative of the guided ballistic-lifting entry mode. Compared with the first-generation unguided ballistic-lifting entry mode utilized during the Viking missions, the guided entry mode adopted in the MSL/Curiosity mission has the capability of achieving a high-precision Mars landing (20×7 km), and represents the future direction of development [36,72,83–85].

1.4. Challenges of Mars atmospheric entry guidance and control

Most previous Mars landing missions adopted the inertial measurement unit (IMU) based dead reckoning navigation mode and the unguided ballistic trajectory entry without aerodynamic lift control, which led to the larger landing error ellipse in the order of several hundred kilometers and cannot meet the requirements of future Mars landing missions [59–62,86]. MSL innovatively extended the EDL technologies developed and tested by the Mars Viking, Mars Pathfinder, and Mars Exploration rover missions, and approached the capability limit of the first-generation EDL technologies. Future Mars missions, such as the Mars Sample Return, Mars base and manned Mars landing missions, need to achieve pin-point landing accuracy (landing error $\sim$100 m). Therefore, the new EDL technologies with more advanced GNC function must be developed for next-generation Mars missions.

It is foreseeable that future Mars missions will benefit from improved approach navigation prior to atmospheric entry. However, even with the best approach navigation available in the near future, the expected dispersions of an unguided ballistic Mars entry can still be in the order of 50–100 km [61,62,86]. The most efficient way to improve the landing accuracy can be achieved during the atmospheric entry by steering the vehicle trajectory to

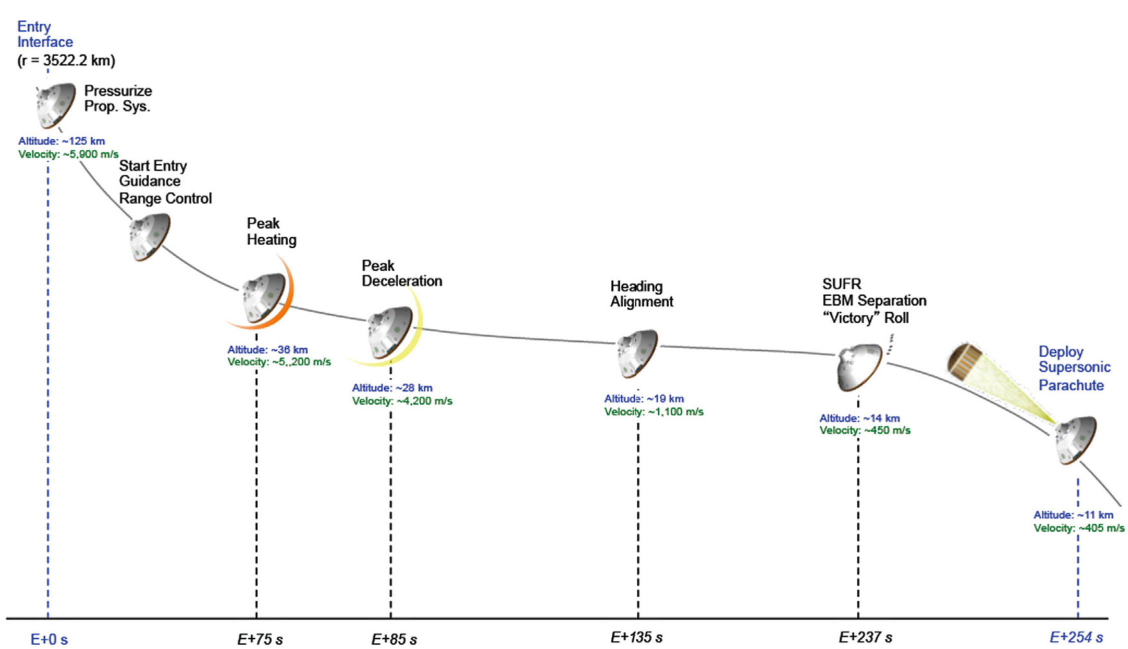


Fig. 2. Sketch of MSL/Curiosity Mars entry [75].

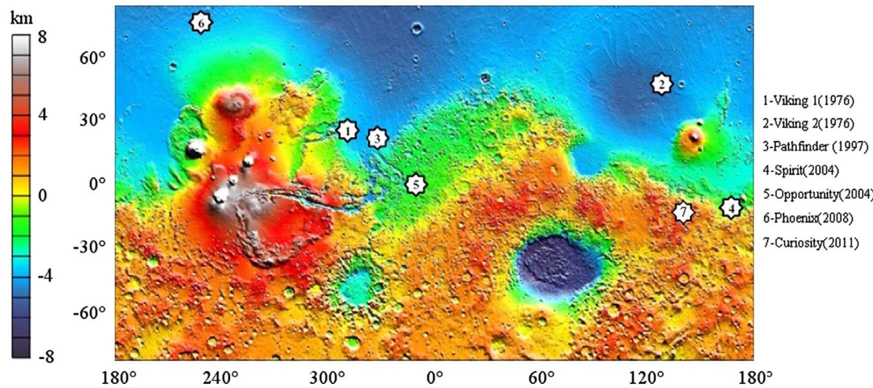


Fig. 3. Mars topographic map and landing sites [80].

eliminate the dispersions caused at entry and accumulated during the hypersonic phase [57,87–89], which was demonstrated by the MSL/Curiosity mission [42,63–66]. Therefore, active closed-loop entry guidance and control techniques are essential for future challenging Mars missions, such as Mars base and manned Mars landing.

The main challenge of Mars atmospheric entry, relative to the Earth entry, is Mars' comparatively thin atmosphere. Martian atmospheric density is only about 1% that of Earth. The thin atmosphere causes the aerodynamic deceleration process of the Mars atmospheric entry phase usually to last a relatively long period of time down to a very low elevation (less than 10 km) [59–61,78,90]. This makes the subsequent descent and landing phases to hav insufficient time and space to achieve the flight path correction, hazard detection and avoidance, position, velocity and attitude desired for a safe [39,40,66]. Because only low elevation landing sites have the necessary atmospheric density to allow a safe landing using current entry, descent and landing technologies, the landing site must be selected at sites with lower elevation in order to take full advantage of aerodynamic deceleration [80]. The landing site distribution of past successful Mars landing missions is shown in Fig. 3. It can be seen that all the landing elevations are below −1.4 km Mars orbiter laser altimeter (MOLA), which leads to the conclusion that half of the surface of Mars with high elevation (in hot color in Fig. 3) cannot be reached using the current EDL technologies [59,80,91,92]. Currently, only the northern hemisphere of Mars is available for landing due to its low elevation. In order to reach most of the Ancient Highlands, the majority of the southern hemisphere, advanced EDL technology is needed in multiple fields, including high-precision entry navigation, active guidance and control [80].

The Mars entry vehicle usually has the low lifting body configuration due to the size limit of the launch vehicle fairing, which leads to a low control authority of the entry vehicle. The double-cone geometry inherited from the Viking program can only provide a lift-to-drag (L/D) ratio as high as 0.3, which means that the magnitude of the lift vector is 30% of the magnitude of the drag vector [80]. At the same time, there are large uncertainties in Martian atmospheric density uncertainties and aerodynamic parameters of entry vehicles, which inevitably degrades the performance of Mars entry trajectory planning, guidance and control [93–95]. The landing error of the first-generation Mars EDL missions is in the order of ~100 km, and the entry vehicles do not have the ability of landing in areas with hazardous terrain and high scientific value [62,83].

Until now, the guidance and control technical challenges for Mars atmospheric entry phase have been addressed from several aspects. The more comprehensive challenges are summarized as follows:

(1) The Mars atmospheric entry dynamics is described by highly nonlinear time-variant differential equations, and the control variables are implicitly included in the equations of motion. Therefore, it is difficult to perform the trajectory optimization and guidance and control design [56,81,96,97].
(2) Relative to the Earth, the Martian atmosphere is approximately 100 times thinner, making it impossible to provide adequate deceleration at high altitudes, and therefore making it difficult for Mars entry vehicles to reach high-elevation sites [80,98–101].
(3) The typical geometry of entry vehicles is a low lifting body configuration that only provides a very small amount of aerodynamic lift and hence a small capability to correct trajectory errors and provide an accurate delivery. The low control authority of entry vehicles inevitably leads to larger entry and landing errors in the presence of uncertainties [80].
(4) There are large uncertainties about the Martian atmosphere and the aerodynamic parameters of entry vehicles. Advanced guidance and control with high accuracy and adaptability are required to achieve high entry accuracy and deliver a vehicle to a high-elevation landing site [94,102]. At the same time, high reliability and fault-tolerant control capabilities are also required to ensure the safety of the crew of future manned Mars landing missions [74,103–107].
(5) The Martian atmospheric environment is rather complex, which makes it hard to be accurately modeled and simulated on the ground. The design process of trajectory planning, guidance and control for Mars atmospheric entry heavily depends on Monte Carlo simulation [108–114].

This paper is structured as follows. Section 1 introduces the background and technical challenge of Mars atmospheric entry guidance and control. Section 2 summarizes the Mars entry guidance and control from the viewpoint of history. Current state-of-the-art and development of Mars entry guidance and control is reviewed and analyzed at length in Section 3. The prospect of Mars entry guidance and control is addressed in Section 4. Finally, Section 5 presents the conclusions.

2. Historical review of guidance and control for Mars atmospheric entry

2.1. Atmospheric entry guidance and control of past Mars landing missions

Just like Earth re-entry vehicles, Mars atmospheric entry vehicles can also adopt the following three different configurations: ballistic, ballistic-lifting and lifting configuration [80,81,96,115–117]. For a ballistic configuration vehicle, there is a smaller total aerodynamic heating, a shorter flight time and range, but a larger peak

heat flow. The entry trajectory of a ballistic configuration vehicle is uncontrollable, which leads to a larger landing error ellipse [115,116]. All the Mars series [2], Pathfinder [7,9,14], Spirit and Opportunity (MER-A/B) [21,24], Phoenix [25,28,33,34], and Beagle-2 [45,46] during Mars entry phase utilized this configuration. Their parachute deployment error and landing error were in the order of ~100 km, while the mass of the entry vehicles was relatively small compared to the vehicles adopting the ballistic-lifting configuration. For ballistic-lifting configurations, a certain angle-of-attack can be produced via the center of gravity offset from the center of pressure, then the entry trajectory can be adjusted by controlling the bank angle and the direction of the lift vector. The maximum overload and dynamic pressure of a ballistic-lifting configuration are relatively low compared to the ballistic configuration. Though the entry vehicle with ballistic-lifting configuration has a certain aerodynamic control capability, the control authority is low and limited. Therefore it cannot effectively reduce the adverse impact of errors and uncertainties, and then improve the landing accuracy in the presence of larger uncertainties [80,81,96]. Both the Viking [3,4] and MSL/Curiosity [36,39,42] launched by NASA utilized the ballistic-lifting configuration. As a certain lift can be produced by this configuration, it makes the Viking the largest vehicle in all first-generation Mars landers except for the recent MSL/Curiosity [6,118]. At the same time, the Viking did not control its flight trajectory by lift adjustment, thus resulting in a large parachute deployment error. Though the aerodynamic deceleration and trajectory control capability of MSL/Curiosity was improved and increased compared to Viking, the burden of the thermal protection system was reduced. Because MSL/Curiosity adopted the advanced entry guidance control technologies, the landing accuracy had been significantly improved [63–66]. The entry vehicle with lifting configuration can produce a large lift with the capability of long-distance maneuver and pin-point landing, which is more suitable for next-generation large mass vehicle entry and landing operations [119–123]. However, it is difficult for Mars entry vehicles to implement in the near future due to the high cost and low reliability.

Three-axis stabilized attitude control was adopted during the Viking atmospheric entry phase by use of the reaction control system, and angle-of-attack was kept at -11° during the entire entry phase. The parachute was deployed when the entry vehicle arrived at the altitude of 5.79 km [3–6]. Though a ballistic-lifting configuration was used in both Viking missions, a guidance function was not included into the entry GNC system, which made the entry trajectories uncontrollable. Therefore, the errors and uncertainties resulted in a larger landing error ellipse. The Mars series [2], Pathfinder [7,9,14] and Beagle-2 [45,46] adopted ballistic unguided entry. Their attitude stability was maintained through a spin velocity that was provided by the cruise stage. As the deviation between actual trajectory and pre-designed trajectory cannot be reduced any more during the atmospheric entry phase, precision navigation at the entry interface is required in order to minimize the errors of parachute deployment and landing. Subsequently, Mars Exploration Rovers also adopted the same entry mode, but a better descent and landing control was used, and thus the landing accuracy was greatly improved [21,24]. Based on the technologies developed during the Viking mission, Phoenix adopted the unguided ballistic entry and RCS to achieve three-axis stabilized attitude control and improve the accuracy of parachute deployment and landing [25,28,33,34]. The MSL/Curiosity inherited the ballistic-lifting entry and three-axis stabilized attitude control from its predecessor Mars smart lander (MSL) [124,125]. A trim angle-of-attack of -15° was used in the atmospheric entry phase [72,82]. At the same time, the Apollo-like entry guidance was included into the MSL entry control system [126,127]. As active guidance and control technology was used to adjust entry trajectory and attitude, the landing accuracy was greatly improved by an order of magnitude. MSL is the only Mars entry vehicle that adopted the guided entry, which succeeded in landing the largest rover Curiosity at the highest landing elevation with minimal landing error [72].

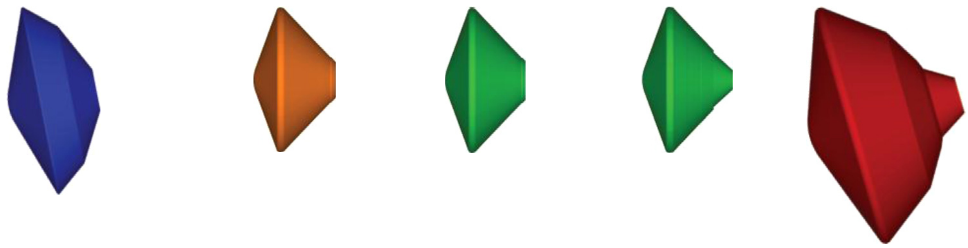
The key entry related parameters of historically proven successful Mars landing missions are systematically summarized in Table 1 [3–35,40–42,44,59,62,67,70,72,75,92]. Because the transmissions of the Mars landers launched by the Soviet Union and ESA soon failed after landing, they are not included in Table 1. It can be seen from Table 1 that the Viking was the only vehicle initiating Mars atmospheric entry from a parking orbit, and other vehicles adopted the direct entry mode. Initial entry velocity of MPF is largest in all seven successful Mars landing missions, reaching 7.26 km/s. In terms of attitude control, Viking, MPF and MSL adopted the three-axis stabilized attitude control by RCS, while MER and Phoenix used the spin-stabilized attitude control method. Both Viking and MSL flew at trim angle-of-attack by the center-of-mass offset to produce a certain aerodynamic lift. MSL is the only entry vehicle that used the active guidance in all seven successful Mars landing missions. It utilized Apollo-derived guidance in the atmospheric entry phase. Compared to the previous Mars landers, MSL topped the previous records of Mars entry vehicles in many respects. They include the largest entry mass of 2920 kg, the largest total landed mass of 1590 kg, the largest rover mass of 900 kg, the largest ballistic coefficient of 115 kg/m^2, the largest lift-to-drag ratio of 0.24, the largest aeroshell diameter of 4.5 m, the largest parachute diameter of 19.7 m, and so on. Due to the most advanced active guidance and control adopted in the atmospheric entry phase to date, MSL succeeded in landing on Mars with the smallest landing dispersion (3σ landed ellipse axis <20 km) and highest elevation ($+1$ km MOLA).

2.2. MSL guidance and control

Though MSL incorporated many techniques from previous Mars missions, it is believed that the entry guidance and control adopted by MSL is the most advanced in all Mars landing missions, and reaches the limit of first-generation EDL technologies developed during the Viking era. Therefore, it is necessary to introduce the MSL/Curiosity guidance and control in detail here.

In order to land a larger rover on the surface of Mars and achieve a more accurate high-elevation landing than all previous Mars landing missions, MSL/Curiosity is the first Mars mission that adopted guided entry with the objective of safely delivering the entry vehicle to a survivable parachute deploy state within 12.5 km of the pre-designated parachute deploy coordinates [75,79,82]. The entry terminal point controller (ETPC) guidance algorithm [128] is derived from the Apollo command module entry guidance [126,127,129], and like Apollo, ETPC modulates the bank angle to control range based on the information of deviations in range, altitude rate, and drag acceleration from a reference trajectory [37–40]. To utilize the aerodynamic lift to control the entry trajectory, the center of mass of the entry capsule is intentionally displaced from its axis of symmetry in order for the capsule to trim aerodynamically with a non-zero angle-of-attack. According to the navigation information from an IMU, the entry guidance algorithm plans the commanded aerodynamic force to track the nominal trajectory, and the control algorithm adjusts the bank angle to track the commanded aerodynamic force by use of RCS thrusters [72]. Then, the entry trajectory can be adjusted by changing the direction of lift vector according to the guidance command. At the same time, the three-axis stabilized attitude control is used to keep entry attitude stability [79,130,131]. Because only tenuous Martian atmosphere can be applied to decelerate during Mars entry, it is critical for the ETPC guidance algorithm to carefully balance the lift of the vehicle to minimize

Table 1
Past successful Mars entry summary [3–35,40–42,44,59,62,67,70,72,75,92].



Entry vehicle	Viking-1/2	MPF	MER-A/B	Phoenix	MSL
Entry form	Orbit	Direct	Direct	Direct	Direct
Initial entry velocity (km/s)	4.7	7.26	5.4/5.5	5.5	5.9
Initial entry flight path angle (°)	−17	−14.06	−11.49/−11.47	−13	−15.5
Ballistic coefficient (kg/m^2)	64	63	94	70	115
Entry mass (kg)	992	584	827/832	600	2920
Entry attitude control	3-Axis RCS	Spin stabilized	Spin stabilized	3-Axis RCS	3-Axis RCS
Trim angle-of-attack (QUOTE)	−11	0	0	0	−15
Entry lift control	Center-of-mass offset	No offset	No offset	No offset	Center-of-mass offset
Entry guidance	Unguided	Unguided	Unguided	Unguided	Apollo-derived guidance
Lift-to-drag ratio	0.18	0	0	0	0.24
Aeroshell diameter (m)	3.5	2.65	2.65	2.65	4.5
Total integrated heating (J/m^2)	1100	3865	3687	2428	6185
Peak heating rate (W/cm^2)	26	100	44	47	208
Parachute diameter (m)	16	12.5	14	11.7	19.7
Chute drag coefficient	0.67	0.4	0.4/0.48	0.62	0.67
Parachute deploy Mach no.	1.1	1.57	1.77	1.2	2.2
Parachute deploy altitude (km)	5.79	9.4	7.4	9.8	6.5
Parachute deploy time (s)	<300	163	241	221	254
3σ landed ellipse major axis (km)	280	200	80	100	20
3σ Landed ellipse minor axis (km)	100	100	12	21	10
Landing site elevation (km)	−3.5	−2.5	−1.9/−1.4	−4.0	+1.0
Total landed mass (kg)	590	360	539	382	1590
Lander/rover mass (kg)	244	92	173	167	900

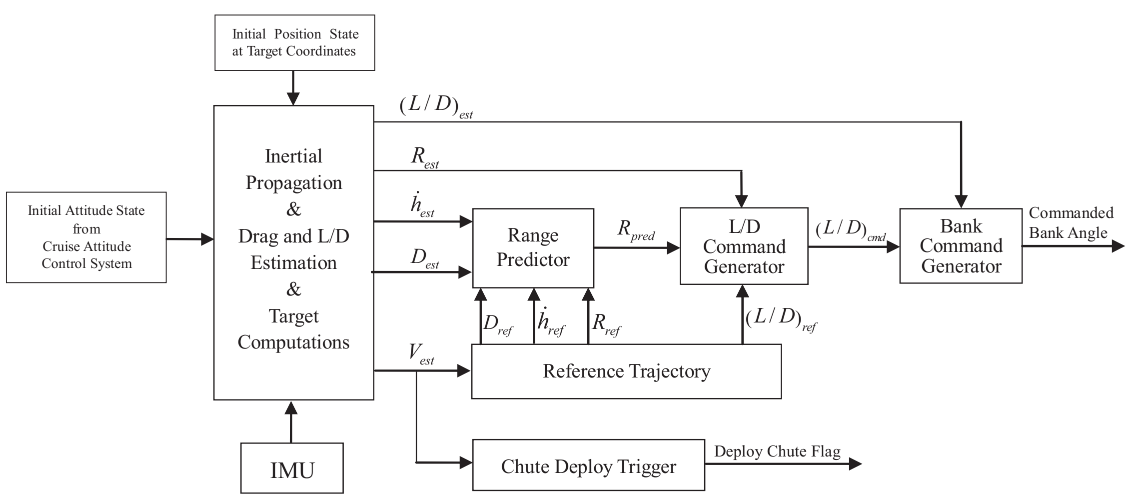


Fig. 4. Architecture of MSL entry guidance [72].

the range error while still ensuring a higher landing elevation and a desired safe parachute deployment altitude. The MSL guidance algorithm consists of two parts: range control and heading alignment [42,72,82]. The system structure of entry guidance and attitude control are shown in Figs. 4 and 5, respectively.

2.2.1. Range control

The range control phase begins when the accelerometers sense 0.2 Earth-g's, and ends when the estimated velocity is less than 1100 m/s. During the range control phase, a predictor-corrector algorithm commands bank angle to adjust the lift force direction in order to control range while keeping cross-range errors within a given corridor by performing, nominally three, bank reversals [72,73,132]. To achieve this goal, the predictor-corrector algorithm, as shown in Fig. 4, utilizes an on-board reference trajectory table, and computes deviations from it according to the state data from the inertial navigator. From those data, the predictor-corrector algorithm makes a prediction of the range-to-go until the conditions for parachute deployment are achieved. The difference between this predicted range and the current range-to-target is the range error that must be corrected. Commanded lift-up is then computed based on the on-board reference trajectory plus a correction proportional to the range error. Finally, the commanded

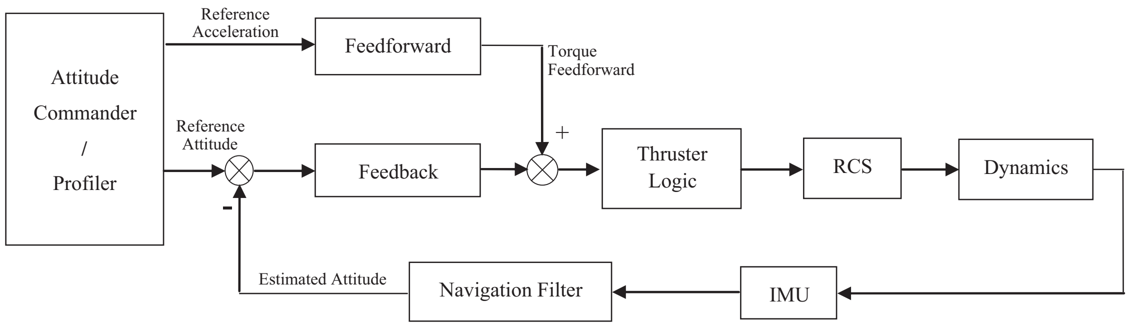


Fig. 5. Architecture of MSL Mars entry attitude control [72,130,131].

lift-up (or L/D to be more specific) is used to compute the commanded bank angle [72,73,75,132,133].

2.2.2. Heading alignment

Heading alignment starts after range control and ends at parachute deployment [72,73]. Once the estimated velocity drops below 1100 m/s, the guidance algorithm automatically ceases range control and begins heading alignment. Entry guidance commands bank angle only to reduce the cross-track position errors that were left from the range control phase, and those that are currently being introduced. Range error is left uncontrolled during this phase, because range control efficacy is diminished when the entry vehicle approaches the prescribed parachute deploy point. The dynamics of cross-range control in heading alignment phase are analogous to the way an airplane controls its heading. The magnitude of the commanded bank angle is limited within 30° to ensure most of the supersonic lift countering gravity to prevent significant parachute deploy altitude loss. Guided entry ends when the sequence of events for parachute deployment is commanded, which includes banking to 180° while jettisoning entry ballast to achieve a trim angle-of-attack near zero just prior to parachute deployment [72,75].

The inertial propagator, which uses the attitude rate and acceleration measurements from the descent stage IMU, provides the estimated vehicle state to the entry guidance algorithm [134]. The attitude state estimate is initialized autonomously from attitude control system (ACS) data of the cruise stage prior to cruise stage separation [79,130,131]. The position and velocity state is initialized from the ground deep space network (DSN) navigation solution, which is computed at the entry minus nine-minutes epoch, and uploaded to the spacecraft. RCS based 3-axis attitude control is utilized to stabilize the entry vehicle and control the direction of the lift vector during the entire atmospheric flight phase. The entry attitude controller, shown in Fig. 5, is implemented as a hybrid proportional-differential (PD) dead-band controller with feed-forward and RCS pulse-width-modulation (PWM). All commanded turns, such as turn-to-entry, bank reversals, turn-to-heading-alignment, are profiled and fed-forward. They were implemented as coordinated turns [72].

3. Current state-of-art of guidance and control for Mars atmospheric entry

Both Mars atmospheric entry dynamics modeling and navigation are closely related to Mars entry guidance and control. Therefore, they are included in the following sections.

3.1. Accurate modeling for Mars atmospheric entry

Dynamics modeling of Mars atmospheric entry is the basis and prerequisite of subsequent reference trajectory planning and guidance navigation and control. The accuracy of modeling will not only affect the fidelity and feasibility of the entry GNC ground simulation and verification, but also affect the accuracy and security of Mars landing [56]. The main difficulty of Mars entry accurate dynamics modeling comes from the fact that there is little observational information about the Martian upper atmosphere, and theMars climate and temperature at high altitude have a great impact on the Martian upper atmosphere. At the same time, there are large uncertainties in the physical and aerodynamic parameters of entry vehicles after a long-time flight. The uncertainties in Martian atmosphere and aerodynamic parameters make it hard to accurately model the aerodynamic forces and moment exerted on the entry vehicle [68,135–137]. So, the accurate Martian atmospheric model is crucial for dynamic modeling and guidance and control design.

Currently, there are two fairly complete Mars atmosphere models available, NASA's Mars-GRAM and ESA's Mars climate database (MCD), and both models are updated annually according to the latest observation data [138–144]. The Mars-GRAM model is developed by NASA's Marshall Space Flight Center, which is the engineering-level high-precision Mars atmosphere model and utilized in the design and analysis of the latest four NASA Mars missions [67,145]. The atmospheric parameters, wind and other related factors are taken into account in this model [139,140]. In order to better approximate the true Mars atmosphere in the various areas and under different climatic conditions, the Mars-GRAM model should be expanded and improved by carefully selecting the appropriate scaling factor [68]. The Mars climate database (MCD) is developed under the funding of ESA, which is also a high-precision Mars atmosphere model. This model was adopted in ESA's Mars Express mission [45–47], and will be adopted by the ExoMars mission in the future [48,49]. The atmospheric parameters, dust, hydrologic cycle and other factors are considered in the Mars climate database (MCD), which can provide the atmospheric data from the surface of Mars to an altitude of 250 km [141–144]. When Mars-GRAM and MCD are applied to predict the parameters of lower height Martian atmosphere, the accuracy of predicting outputs is high and the prediction error is less than 5%. However, the deviation is relatively large and even up to 15% if adopted to predict the Martian upper atmosphere [138–144]. Because both models are too complex and involve many parameter inputs, the simplified model based on exponential function fitting is usually utilized for the initial mission design and analysis [56,96,146]. However, the simplification inevitably degrades the accuracy of the model. In order to improve the accuracy of Mars atmosphere models, more accurate observational

data is needed to further improve the existing models [147,148]. At the same time, suitable approaches are also sought to simplify the model without excessive loss of accuracy [149].

In fact, there are two basic approaches to improve the accuracy of Mars entry dynamics models [149–151]. One approach, as mentioned above, is to improve the accuracy of the Mars atmosphere model. Another more effective way is to real-time measure the flight state parameters of entry vehicles [152–154]. The MSL Entry, Descent, and Landing Instrument (MEDLI) suite was developed in the MSL/Curiosity mission [155–157], which can measure the real-time data of the dynamic pressure, temperature, Mach number, angle of attack, bank angle and atmospheric density using the temperature and pressure sensors on back of the heat shield of the entry vehicle. Then, the more accurate entry dynamic characteristic parameters can be determined based on these real-time measurement data, which results in significantly improving the accuracy of Mars entry dynamics modes. Following this approach, Tolson et al. [158] further proposed the innovative idea of online modeling, which has the ability of effectively eliminating the adverse effects of inaccurate modeling during the mission design.

3.2. Trajectory planning for Mars atmospheric entry

Mars entry trajectory planning is an important prerequisite for the implementation of guidance and control [74,159,160], and considered as one of the key technologies for future Mars landing missions. On the one hand, it can increase the safety of the EDL mission. For example, when some faults occur during the Mars entry phase, a contingency trajectory can be quickly planned, and thus the entry vehicle still can be guided to achieve a safe landing, which is essential for a manned Mars landing mission [104–107]. On the other hand, it can provide the entry process with more operational flexibility and reduce the burden of control system design [62]. Mars atmospheric entry trajectory planning is essential to solve an optimal control problem with complex state and boundary constraints, and the solving approaches can be divided into two categories: indirect and direct methods [160,161].

3.2.1. Indirect method

The indirect method utilizes the maximum principle to solve the optimum control problem by introducing conjugate variables. The shooting method or multiple-step shooting is a typical representative of the indirect method. The merit of the indirect method is the high accuracy of the solution, if obtained. At the same time, it has obvious disadvantages. The indirect method is sensitive to the initial guess, which leads to a small convergence domain. Because the initial values of conjugate variables have no clear physical meaning, the initial guess is difficult to obtain. In order to find a proper initial guess, the repeated iteration and integration of state and co-state equations are inevitable, which of course renders the real-time of the indirect method poor and difficult to be directly applied to the online trajectory optimization of Mars atmospheric entry [62,161].

3.2.2. Direct method

The direct method transfers the entry trajectory planning problem into a static parameters optimization problem with various path and boundary constraints, which can be easily solved by a nonlinear programming (NLP) algorithm [162]. Both the direct collocation method and the pseudo-spectral method are typical representatives of the direct method. Due to ease of implementation, the direct method has been widely adopted in engineering practice, especially in the field of trajectory optimization.

Li et al. [160] proposed a trajectory optimization method for Mars entry based on the desensitized optimal control and direct collocation nonlinear programming, in which the uncertainties in aerodynamic parameters and the performance of trajectory tracking were integrated considered. Since the planned nominal trajectory is not sensitive to uncertainties and disturbances, the difficulty of tracking guidance is greatly reduced for a low lifting entry vehicle. Ren et al. [163] developed the rapid trajectory optimization algorithm for Mars pin-point landing using the hp-Radau pseudo-spectral algorithm. The problem of trajectory optimization was converted into a large-scale parameters optimization problem with multi-constraints by the hp-Radau pseudo-spectral algorithm [164]. The vehicle dynamics, state and safety constraints were taken into account in their planning. In order to improve the efficiency of the algorithm, the analytical form of the Jacobian matrix of performance index and constraint equations were derived.

The recent development of pseudo-spectral methods has enabled the mapping of results between direct and indirect methods. Benson [165] pointed out that the Karush–Kuhn–Tucker (KKT) conditions of Gauss pseudo-spectral method are equivalent with the one order optimality conditions of the maximum principle. After that, various pseudo-spectral methods (Legendre pseudo-spectral method, Radau pseudo-spectral method and Gauss pseudo-spectral method, etc.) were developed in recent years and applied to the problem of trajectory optimization [163,166–169]. One disadvantage of the pseudo-spectral approach is that this method heavily depends on the designer's experience to select the suitable number of nodes, because there are no clear fixed node selection rules. Additionally, pseudo-spectral methods usually adopt a higher-order polynomial to fit the state variable and the control variable at the fixed node and collocation points, and the distribution of nodes is relatively fixed for a given number of nodes. If a system involves the state or control variables with non-smooth or large curvature, the number of nodes in the entire space needs to be increased in order to ensure the fitting accuracy, which inevitably degrades the calculation efficiency of the entire algorithm [170,171]. The Mars entry process usually involves several bank angle reversals [72,130,131], which result in the state curves and control curves to have greater curvature when bank angle reversal is executed. Therefore, in order to meet requirements of a future Mars high-precision landing mission, it is essential to improve the original pseudo-spectral optimization method by considering the balance between real-time and accuracy.

3.2.3. Intelligent algorithm

In order to overcome the problem of initial guess, intelligent global search algorithms, such as genetic algorithms [172] and particle swarm optimization [173–175], were introduced in recent years to solve the trajectory optimization problem for Mars entry. Sorgenfrei and Chester [172] proposed a strategy for the high-level search for entry, descent, and landing system solutions by means of a genetic algorithm. A functional implementation tool, called the Parametric Entry, Descent, And Landing Synthesis (PEDALS), leverages the stochastic search process of a genetic algorithm efficiently to search for a broad swath of candidate design solutions. The aim is to examine the suitability of an evolutionary method as an aide to early design trades. Grant and Mendeck [174] discussed the reference trajectory design using particle swarm methodology to improve upon the manual, time consuming traditional design method. A single objective particle swarm optimization (SOPSO) algorithm and a multi-objective particle swarm optimization (MOPSO) algorithm were developed. The SOPSO algorithm was used to validate the capability of applied swarming theory to Mars entry optimization. The MOPSO algorithm is an extension of SOPSO, providing the capability to

generate Pareto fronts in the environment of competing objectives. The Pareto fronts generated by MOPSO provided quick insight into the design characteristics of Mars entry trajectory that took a long time to understand through the traditional point design process. The optimal trade associated with the conflicting objectives of supersonic parachute deployment altitude, range error ellipse length, and g-loading were quantified in a visual environment. Though the global optimal solution can be obtained by an intelligent global search algorithm, it comes at the cost of a large number of iteration calculations and poor real-time.

3.2.4. Uncertainty propagation

Due to the large uncertainties in the state variables at the entry interface, Mars atmospheric density and aerodynamic parameters, there usually exists much delivery deviation between the actual landing site and the designated target. To ensure safe landing for next-generation Mars exploration missions, in which the capability of landing spacecraft in hazardous areas with high scientific value will be required, it is essential to assess the impact of the uncertainties on state trajectories, and to determine the error ellipse of the supersonic parachute deployment site and the final landing site [80,176,177].

To assess the performance of the vehicle configurations and trajectory planners, Benito and Mease [176,178] proposed the concept of reachable and controllable sets for Mars atmospheric entry, which can be used to comprehensively characterize the envelope of trajectories that a vehicle can fly, the sites it can reach and the entry states that can be accommodated. These sets can also be used for the evaluation of trajectory planning algorithms and to assist in the selection of the entry or landing sites. In essence, the reachable and controllable sets offer a powerful vehicle and trajectory analysis and design framework that allows for better mission design choices. Ren et al. [169] analyzed the state trajectories' evolution of a Mars entry vehicle in the presence of larger uncertainties in initial conditions and other system parameters. By introducing uncertainty factors, they converted the stochastic dynamical systems into the equivalent deterministic dynamical systems in a higher-dimensional space. Then, a rapid uncertainty propagation method was obtained based on the local linearization and linear system theory. Simulation results indicated that the proposed method, compared with traditional Monte Carlo method, could predict the evolution of uncertainty with little degraded accuracy and much more computational efficiency. Because the linearization method was utilized to propagate the uncertainties, it may be unsuitable for the Mars atmospheric entry phase with larger uncertainties. Prabhakar et al. [179,180] presented a novel computational framework for analyzing the evolution of uncertainties in state trajectories of a hypersonic air vehicle due to the uncertainties in the initial conditions and other system parameters. Zhu et al. [177] adopted Prabhakar's approach to analyze the uncertainty propagation issues during the Mars atmospheric entry phase. In their approach, the Polynomial Chaos (PC) method was used to approximate the vehicle's states, then the problem was converted to a deterministic dynamical system in a higher-dimensional space by introducing the Galerkin projection. To avoid the breaking down of the generalized polynomial chaos caused by long-time integration, new stochastic variables and the set of orthogonal polynomials were constructed with respect to the changing probability density as time progressed. The uncertainty sources they considered included initial condition, ballistic coefficient, lift over drag ratio, and the atmospheric density [177]. It was shown that the results agreed very well with Monte-Carlo simulations, but with more computational efficiency.

3.3. Traditional guidance for Mars atmospheric entry

The objective of Mars entry guidance is to steer an entry vehicle from atmospheric entry interface to a designated parachute deployment target at the end of the entry phase with certain accuracy [58,181,182]. However, there are many uncertainty factors and errors that will degrade the performance of the guidance algorithm in engineering practice. The most significant error sources leading to a larger Mars entry dispersion include the vehicle state estimation errors at the atmospheric entry point, the uncertainties in the atmospheric density and aerodynamic coefficients, and the winds and gusts [183–185]. It was demonstrated that the most efficient way to increase the entry accuracy is steering the entry trajectory to eliminate the adverse impact of the uncertainties and errors [186–188]. It is believed that the next-generation Mars entry vehicles, such as the vehicles for future HERRO mission, Mars sample return, manned Mars mission, will basically inherit the ballistic-lifting configuration and guided entry mode developed by MSL mission [73,189–192].

Despite the fact that a few Mars entry guidance laws were designed by simultaneously controlling the angle-of-attack and bank angle to achieve more satisfactory control, adding the angle-of-attack actuation not only leads to more complicated guidance algorithms but also brings about many technical challenges in engineering implementation [193,194]. For example, bank angle control can be easily achieved only using a reaction control system, while adjusting angle-of-attack requires body flaps or multiple axis center of gravity (CG) shifting [185]. Therefore, bank angle modulation only is often adopted in practice to steer the vehicle during Mars atmospheric entry in order to simplify guidance law design and facilitate engineering implementation, while angle-of-attack is kept trim (or constant) to ensure the required lift-to-drag ratio. Through the method of bank angle modulation, the entry vehicle can manage energy and downrange to target [195,292]. One default of only modulating bank angle is that the Mars thin atmosphere and the low lift configuration of entry vehicles lead to the available control force to be limited [196].

Generally speaking, Mars atmospheric entry guidance methods can be divided into two categories: reference-trajectory tracking guidance [197–199] and prediction-correction guidance [200,201–206], and each of them has certain advantages and disadvantages [207]. In the former guidance mode, an optimal reference trajectory is planned according to specific performance indexes and constraints in advance. Then, a controller is designed to track the reference trajectory. In the latter guidance approach, the terminal state can be firstly predicted according to the entry dynamics model and current state variables of the entry vehicle. Then, the predicted state variable is utilized to compare with the desired terminal state to produce the tracking error, which is treated as the feedback to correct the tracking errors.

3.3.1. Reference-trajectory tracking guidance

In order to reduce the dispersions caused at entry interface and accumulated during the Mars atmospheric entry, the tracking guidance law for the low lift-drag ratio vehicle was designed by use of the linear quadratic regulator (LQR) [208]. Steinfeldt and Tsiotras [209] utilized the state-dependent Riccati equation control for closed-loop guidance of the Mars atmospheric entry phase. An innovative approach of sum-of-squares programming was adopted to solve the state-dependent Riccati equation with application of a state-dependent Riccati equation derived guidance algorithm to a high-mass robotic Mars entry mission. A linear-quadratic regulator was utilized to obtain the state-dependent Riccati equation control law. Wu et al. [210,211] applied the extended high-gain state and perturbation observer and feedback linearization techniques to the drag tracking guidance for Mars entry. The observer estimated the drag, the drag rate and the perturbation due to model uncertainty and disturbance for drag

tracking. As the Mars entry dynamics is a highly nonlinear and time-varying process with larger uncertainties, the tracking guidance law based on LQR and feedback linearization will inevitably lead to larger delivery errors.

A number of entry guidance schemes involve the tracking of an aerodynamic drag profile via adjustments to the vehicle bank angle [291]. The available lift, namely the control authority, is limited and saturation is likely to occur, especially for the entry vehicles with low lift-to-drag ratio. Tracking guidance laws derived from approximate, or feedback linearization of the drag error dynamics, may perform poorly in the event of saturation. To improve the performance of tracking laws in the case of saturation, Benito and Mease developed the nonlinear predictive controller (NPC) based drag tracking entry guidance [212]. The bank angle command at each guidance cycle was the value that minimized a prescribed cost function. The cost function took into account the errors in drag and drag rate, as well as downrange (specifically trajectory length) error. There was also additional logic that modified the tracking law to consider cross-range targeting. Benito and Mease developed the entry guidance algorithm that allowed high-elevation landing and provided as well high landing accuracy [213]. The approach taken followed the acceleration guidance approach successfully utilized in missions like the Space Shuttle. Based on this approach, a new planner had been developed that was computationally fast and provided the trajectories with both high final altitude and high control authority [214]. The nonlinear predictive control based tracking law developed in [212] was utilized to track the reference trajectory. The new entry guidance algorithm accounted for control saturation, which was a common feature of trajectories in the thin Martian atmosphere with a low lift vehicle.

In order to suppress the adverse effect of uncertainties in atmospheric density and improve the entry guidance accuracy, sliding mode variable structure control (SMVSC) [215,216] and multiple sliding mode surface guidance (MSMSG) [217] were adopted to design the Mars entry guidance law, respectively. Though the SMVSC and MSMSG approaches have the better adaptivity to uncertainties, and can ensure the guidance accuracy in theory, both are developed based on the assumption that the unknown uncertainty be bounded and that the bounds be known in advance, which make it difficult to realize in practice. Additionally, tremors with SMVSC or MSMSG usually lead to poor guidance and control effect. Adaptive on-board entry guidance algorithms were developed in order to reduce the impact of uncertainties during Mars atmospheric entry [218–222]. Their main ideas of algorithms are roughly the same. A reference trajectory is firstly planned subject to various constraints, then an adaptive feedback control is used to track the reference trajectory. Following this idea, the Evolved Acceleration Guidance Logic for Entry (EAGLE) guidance method [80,159] developed by NASA consists of two main functions, a reference-trajectory planning function and a tracking function that commands bank angle and angle-of-attack to follow the planned reference trajectory. EAGLE has its heritage in the Apollo and Shuttle programs, which plan and track aerodynamic accelerations [159]. In essence, entry terminal point controller (ETPC) guidance, adopted in MSL atmospheric entry, also belongs to a category of reference-trajectory tracking guidance, which has been introduced at length in Section 2.2 and therefore is not addressed here [128].

3.3.2. Predictor-corrector guidance

Lévesque and Lafontaine [194,223] developed two analytical predictor-corrector guidance algorithms using two density-relative flight path angle profiles for Mars atmospheric entry to achieve the desired terminal altitude, velocity and downrange. The first algorithm utilized two constant flight path angle segments in order to meet the terminal altitude, velocity and downrange requirements [223]. The second was based on a single density-proportional flight path angle segment [194]. The guided trajectories from both algorithms were close to the ballistic flight trajectories to maximize the control authority of the bank angle on the lift vector. Kozynchenko [224] provided the detailed analysis of the applicability of predictive guidance technique at the entry phase with the focus on functioning under high atmospheric and aerodynamic uncertainties, and showed the accuracy limitations inherent in the investigated predictive guidance algorithms [291]. The predictor-corrector guidance algorithm was developed for determining roll reversals during Mars entry, which needed a precise dynamics model to predict the final state variables [225]. Unfortunately, the uncertainties of Martian atmospheric density, ballistic coefficient and other factors will lead to an inaccurate dynamics model. In order to reduce the computational burden of the predicting process, Wang [226] introduced the fuzzy logic to design the longitudinal guidance. As the fuzzy logic design process heavily depends upon personal experience, Wang's approach must be improved before it can be used for precision-guided Mars entry. The predictor-corrector and its improved algorithms were used to determine the reverse logic of bank angle during the atmospheric entry process [201–206,231], but all these algorithms required accurate dynamics model and large calculation capability. Therefore, the predictor-corrector guidance algorithms reported above may be unsuitable for Mars atmospheric entry phase with larger uncertainties and limited onboard computing capacity [207].

3.3.3. Comparative analysis

As discussed above, both reference trajectory tracking guidance and predictor-corrector guidance have their advantages and disadvantages [207]. The advantage of reference-tracking guidance is simple and easy to be implemented. The disadvantage lies in the fact that it is developed based on linear assumption, and a high-performance controller is required to track the reference trajectory. Because Mars entry dynamics is a highly nonlinear system, the reference trajectory is usually hard to be accurately tracked, especially in case that there are larger errors in the cross-range and heading angle. The advantage of predictor-corrector guidance is that it can automatically adjust the predetermined flight trajectory and thus reduce the entry error according to the real atmospheric environment and the real-time state variables of entry vehicles. Predictor-corrector guidance has a good adaptability to Mars atmospheric entry compared to reference-tracking guidance, but it requires a precision dynamics model to predict the terminal states of entry vehicles. Predictor-corrector guidance algorithms can handle most flight conditions at the expense of requiring fast on-board computation, accurate aerodynamic and atmospheric models and a simple parameterization of the control. Because of the reference trajectory computing prior to the entry, reference-tracking guidance algorithms are less flexible to accommodate different flight conditions, but do not require fast on-board computation and can be designed to have some degree of model-independence [80].

Although the accuracy of predictor-corrector guidance is generally better than that of the reference-tracking guidance, in the case that both the accuracy of entry dynamics model and onboard computing performance cannot meet the requirements, predictor-corrector guidance is difficult to be applied in engineering practice [175,199]. Therefore, the reference-tracking guidance is still the preferred scheme for the near-future Mars landing exploration missions. To further improve the adaptability and robustness of reference-tracking guidance, the following two aspects need to be

improved. First, the controller of trajectory tracking needs a certain degree of robust adaptive capability. Second, fast online trajectory planning is required to ensure that the entry vehicle can re-plan a new optimal reference in the case of large tracking error. In order to meet requirements of future lager mass Mars pinpoint landing missions, predictor-corrector guidance is essential. A set of MEDLI suite was used in the MSL mission, which can effectively measure the aerodynamic parameters of the entry vehicle in real time [155–158]. Therefore, the accuracy of Mars entry dynamics models can be significantly improved, and thus the accuracy of Mars entry predictor-corrector guidance was correspondingly improved. It is believed that the online aerodynamic measuring approach will accelerate the application of the predictor-corrector guidance in practice. Furthermore, multidisciplinary guidance design for entry vehicles [175] is also an important direction for future research.

3.4. Robust and adaptive guidance and control for Mars atmospheric entry

As there are large uncertainties in the Mars atmospheric environment and entry aerodynamic characteristics, it is more difficult for the flight control system to track the guidance commands and reference trajectory. To achieve the desired requirements of high-precision guidance and control, more advanced guidance and control methods are needed [213,227–229]. At the same time, it is a primary prerequisite to protect the safety of the astronauts for any manned space missions. In order to improve the reliability of any Mars entry control system, fault tolerance capacity is required for future manned Mars missions [230]. To this end, advanced control theories and methods, such as nonlinear control [212,231], robust control [223,232–234], adaptive control [102,235–239], neural network control [95,240,241], have been applied to the Mars atmospheric entry guidance and control. Hormigo [231] and Kranzusch [241] utilized dynamic inversion control and neural network to online approximate the uncertainties in the Mars entry model, then the error caused by uncertainties can be effectively compensated. Li et al. [95] extended the work in [215,216] and developed the neural network-based sliding mode variable structure control (NNSMVSC) algorithm for Mars entry, which effectively reduced the impact of uncertainties and improved the guidance accuracy. Robust sliding mode variable structure control (SMVSC) was used to track the pre-designed nominal trajectory in longitudinal plane, and neural network was adopted to approximate the uncertain terms in the SMVSC. de Lafontaine et al. [223,232] developed several control algorithms for Mars entry by use of robust control. These algorithms had the ability of accurately tracking a predetermined trajectory or guidance commands while maintaining a stable attitude, but the uncertainties of Mars entry process were not taken into account. Model reference adaptive control and Structured Adaptive Model Inversion Control (SAMIC) were utilized in the Mars entry, which effectively overcame the impact of parameter uncertainties and improved the robustness of entry guidance [239]. After that, Li et al. [102] developed the Command Generator Tracker (CGT) based direct model reference adaptive tracking control algorithm to eliminate the effect of the bounded uncertainties and disturbance during Mars entry and steer the entry vehicle to the pre-designed target. This guidance algorithm was a simple adaptive control method based on output feedback. Both adaptive observer and full state feedback were removed. This tracking control strategy is easily implemented on the low-cost, low-weight entry vehicle from a practical point of view, because it requires only storing a set of pre-computed control parameters and a nominal trajectory on board.

It is necessary to consider the reliability of the guidance and control system when the manned Mars missions are taken into account. To improve the reliability of Mars entry guidance and control, Marwaha and Valasek [230,242–244] developed three sets of fault-tolerant control allocation algorithms based on adaptive control theory. Adaptive control was adopted to overcome the uncertainties during the Mars entry process, while the discrete control allocation method was utilized to reconstruct the faulted actuators and control. Then, the influence of control failure was significantly reduced, and the basic performance of trajectory tracking was maintained, which is vital for a manned Mars mission. Currently, there is little published literatures in the field of Mars entry adaptive fault-tolerant control, which is essential for next-generation Mars EDL missions.

3.5. High-precision autonomous navigation for Mars atmospheric entry

The accuracy of guidance and control largely depends on the accuracy of navigation outputs [245,246]. Traditional Mars entry vehicles adopt IMU based dead reckoning navigation without the correction from available external measurement, which leads to larger navigation error due to the bias and drift of inertial sensors [247,248]. Even though the most advanced guidance and control technologies are adopted in the MSL/Curiosity, the final landing error ellipse is still more than ten kilometers [249,250]. Therefore, the high-precision autonomous navigation capability is required in order to improve the accuracy of entry guidance and control and meet the requirements of future Mars pinpoint landing missions.

Generally speaking, there are three basic ways to improve the navigation accuracy during the Mars atmospheric entry phase [146,251]. The first effective approach is to correct the inertial basis and drift using external measurement. To this end, the existing or potential Mars orbiting beacons, such as the functional orbiters and proposed Mars Network [252–256], can be used to perform integrated navigation [146,257]. Recent research shows that the ionizing plasma around the entry body has little effect on ultra-high frequency (UHF) band (300–3000 MHz) radio communication, which can be utilized in real-time to significantly improve the on board state knowledge during the Mars atmospheric entry phase [252,254]. The entry integrated navigation using orbiting beacons has been addressed in the last decades. Lévesque and Lafontaine [56,258] studied the navigation performance and observability of four measurement scenarios based on radio ranging during the Mars atmospheric entry phase. Li and Peng [146] preliminarily discussed the issue of Mars entry navigation using IMU and orbiting/surface radio beacons. The effect of a radio blackout on navigation outputs was also taken into account. Fig. 6 depicts the schematic diagram of radio beacons/IMU integrated navigation. They found that the inertial constant bias and drift can be effectively suppressed and eliminated by fusing the range and velocity information from the entry vehicle to the orbiting and surface beacons to correct, and then a high-precision entry navigation can be achieved even if there is radio blackout. However, both Li et al. [146] and Lévesque et al. [258] did not discuss the issue of the high-precision Mars entry navigation under large uncertainties. The navigation measurements were processed using an unscented Kalman filter and an extended Kalman filter respectively, which lacks the robust adaptive capability and cannot achieve a higher navigation accuracy in the presence of larger state errors and parameter uncertainties. There are larger uncertainties in the Martian atmosphere and aerodynamic parameters, which degrade the performance of navigation filter. Therefore, the second approach of improving the navigation accuracy of Mars atmospheric entry is to develop robust adaptive filter algorithms to suppress the adverse impact of uncertainties [259–262]. In order to overcome the adverse effects of uncertainties in the Martian atmospheric density, Heyne and Bishop [263]

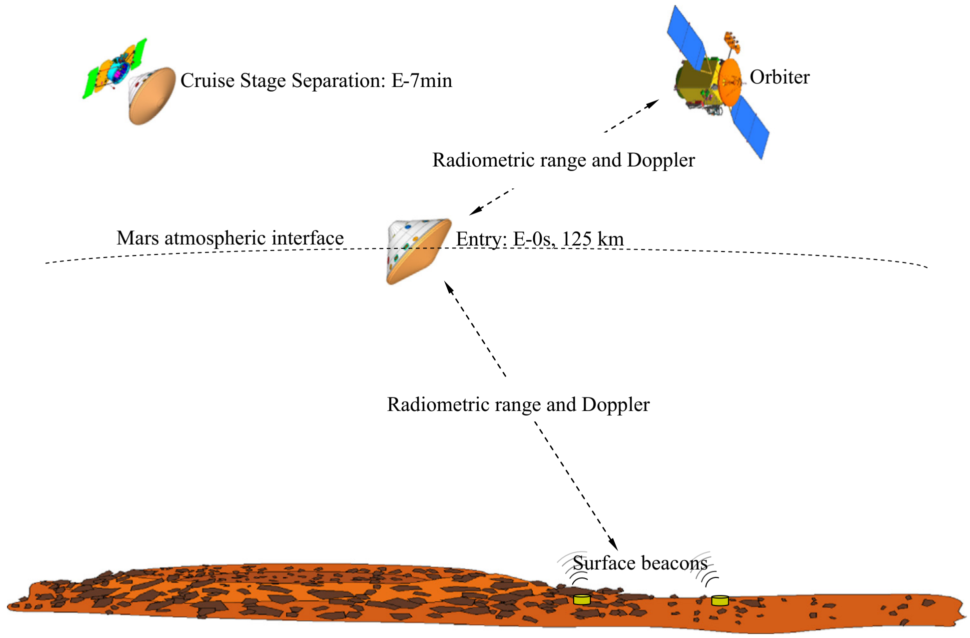


Fig. 6. Schematic diagram of radio beacons/IMU integrated navigation [146].

adopted an adaptive sigma point Kalman filter bank to achieve spacecraft precision entry navigation in the presence of a highly dynamic environment with noise and unknown forces. Ely and Bishop [264] applied the hierarchical mixture of experts' architecture to Mars entry navigation, in which the navigation filters are parameterized with various atmospheric and other spacecraft parameters. Zanetti and Bishop [265] investigated the application of a multiple model adaptive estimation architecture to entry navigation during the highly dynamic hypersonic entry phase. The work reported in [146] was subsequently extended by Li et al. [257], who utilized the desensitized extended kalman filter (DEKF) to Mars entry integrated navigation. Then the navigation accuracy can be greatly improved in the presence of large uncertainties. Last but not least, a more accurate entry dynamics model can be developed and embedded in the navigation filter in order to improve the accuracy of navigation outputs. A new six degree-of-freedom (DOF) Mars entry dynamics model was derived based on the angular velocity outputs of a gyro. Because the state variables of the entry vehicle are directly reconstructed from IMU measurements free of uncertainties in atmospheric density and aerodynamics parameters, a more complete and accurate description of the state variables of the entry vehicle than the traditional three DOF dynamics models [146,266] can be obtained.

4. Prospect of guidance and control for Mars atmospheric entry

Future Mars landing exploration missions will include Mars sample return, manned Mars landing, and Mars base missions. In order to ensure the mission success, the next-generation entry vehicle must have the capability of accurately landing a large mass vehicle/rover on a high-elevation landing site [59–62,98,106]. In the manned Mars landing mission, the landing mass may be up to 20–100 t, and the landing error is required to be limited to 0.1–1 km. In order to ensure that more than 95% of the surface of Mars terrain is reachable, the landing elevation must be higher than +2 km [75,267]. At the same time, a high reliability entry guidance and control system is required for manned Mars missions [104–107,268,269]. The current Mars EDL guidance and control cannot meet the requirements of future Mars landing missions. Therefore, a series of key EDL technologies must be developed, including high precision and high reliability Mars entry guidance and control technologies.

Combining the current state-of-art of Mars entry guidance and control technologies and future requirement for Mars pin-point landing missions, we address the possible solutions and key technologies of Mars entry guidance and control from the following six aspects.

(1) A dynamic model is utilized not only in the Mars entry guidance and control system but also in the entry navigation filter, which is the foundation and prerequisite to achieve high-precision Mars entry guidance and control. In order to meet the demands of accurate dynamics modeling for future Mars landing missions, attention should be paid to the online modeling and calibration technique, which can be used to measure aerodynamic parameters and then significantly improve the accuracy of the model. MSL adopted the atmospheric date sensor MEDLI to real-time measure the dynamic pressure, temperature and Mach number, which can be retained and developed for future Mars entry vehicles [155–157]. At the same time, the higher-order Mars gravity field, Mars rotation and the Coriolis force and other factors should be taken into account in the course of modeling to improve the accuracy of Mars entry dynamics.
(2) The control authority of Mars entry vehicles is low due to the thin Martian atmosphere and small lifting body configuration. The tracking control law cannot accurately follow the pre-planned nominal trajectory when there are large uncertainties in the atmospheric density and aerodynamic parameters, which leads to degraded guidance performance. There are two potential approaches worth further studied in order to solve this afore-mentioned problem. The first approach is fast online trajectory re-planning. If the entry vehicle has the ability to re-plan the reference trajectory when there is a larger tracking error, the performance of reference-trajectory tracking guidance can be greatly improved. The second approach is the integrated design approach using a reference trajectory optimization and tracking control law [74]. The basic

idea of the integrated design approach is that the performance index of a tracking control law is included in the index of reference trajectory optimization, then the two separate design processes (reference-tracking) are now integrated into one design process and simultaneously performed. Because the tracking ability and performance are involved in the optimization index, the default of traditional reference tracking guidance can be effectively avoided and the tracking performance can be significantly improved. It is believed that the integrated design approach has better performance and is more suitable for future Mars entry guidance when compared to the approach of fast online trajectory re-planning.

(3) Due to the guidance and control system working throughout the whole process of Mars atmospheric entry phase, its performance is directly related to the success of the whole Mars mission. As a Mars atmospheric entry dynamic model is a fast time-varying system with large uncertainties and disturbances, it is difficult for a traditional guidance and control approach to achieve a pin-point Mars landing. Therefore, advance guidance and control are required for next-generation Mars EDL missions. In essence, robust adaptive control and intelligent control are proposed and developed to handle a variety of uncertainties and disturbances included in a dynamic system [60,182,218]. At the same time, next-generation Mars missions, such as manned Mars missions and Mars base missions, need a guidance and control system with high adaptivity and reliability to ensure the safe return of the astronaut crew to the Earth in case of partial malfunction of entry vehicles [242]. It is believed that adaptive guidance and control with fault-tolerant capability are the future direction of next-generation Mars EDL.

(4) The performance of entry guidance and control heavily depends on the accuracy of navigation outputs. Traditional Mars entry adopts inertial measurement unit based dead reckoning navigation and leads to large navigation error. In order to achieve the pin-point landing, high-precision autonomous navigation must be developed for future Mars missions. To this end, integrated navigation, such as external measurement aided inertial navigation, can be utilized to correct the inertial basis and drift and then improve the accuracy of Mars atmospheric entry autonomous navigation. The difficulty lies in the fact that most external sensors cannot work in this phase due to heavy aerodynamic heating. With the continuous progress of Mars missions, there will be more and more orbiters launched into Mars orbit in the future. Therefore, the proposed Mars Network, like GPS around the Earth, will come into existence in the near future. IMU/radio integrated navigation or satellite navigation should be emphasized because they can provide the high-precision navigation outputs vital for future pin-point Mars landing missions.

(5) Because the deceleration and maneuvering capability of Mars entry vehicle is very limited due to the thin Martian atmosphere and low lifting configuration, it is difficult for traditional deceleration mode to meet the requirements of the guidance and control for future large mass entry vehicles [270,271]. In order to increase the aerodynamic force for entry control and thus achieve better trajectory and attitude control authority for future Mars precision landing missions, innovative deceleration techniques must be developed [272,273]. To this end, three kinds of alternatives, supersonic braking thrusters, umbrella-like aeroshell, and inflation aeroshell have been proposed. In the first scheme, thrust vectors are utilized toward the heading direction, and then the entry attitude and trajectory can be adjusted by controlling the thrust vector [274–277]. Many experiments show that the jet of thrusters will not only affect the pressure distribution on the surface and the attitude stabilization of entry vehicles during the hypersonic entry process, but also increase the burden of the thermal protection system [278–280]. The second alternative approach is the umbrella-like aeroshell, which is composed of the foldable heat-resistant skin, link mechanism and driving device. Umbrella-like aeroshells can be used for enhancing atmospheric capture and aerodynamic deceleration as well as trajectory and attitude adjustment during the entry and descent process [269,281]. However, this system has a relatively complex structure with large mass, which limits its potential applications. The third one is the inflation aeroshell, which can effectively reduce the ballistic coefficient of entry vehicles by air inflating and then increase the drag coefficient and reference area [282–287]. The desired aerodynamic lift and drag can be obtained by carefully designing the shape of the inflation aeroshell. The aerodynamic deceleration can be gradually controlled by adjusting the center of gravity (CG) for large mass entry vehicle [286,287]. The advantage of this approach is simple in structure, and easy to perform. Recently, inflation aeroshell technology has been successfully tested and verified at Mach 5. With the development of material science [288–290], the inflation aeroshell could be used for the whole process of Mars hypersonic entry [285]. Therefore, the inflation aeroshell has a better application prospect in the near future when compared to the other two alternative approaches.

5. Conclusions

Past Mars landing missions showed that active guidance and control play an irreplaceable role in the Mars atmospheric entry phase, and directly determine the success of the entire Mars exploration mission. The first-generation Mars EDL technologies developed by the Viking mission cannot meet the accuracy and reliability requirement of future pinpoint Mars landing missions. Therefore, advanced guidance and control technologies with desired robust adaptive capability need to be developed.

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